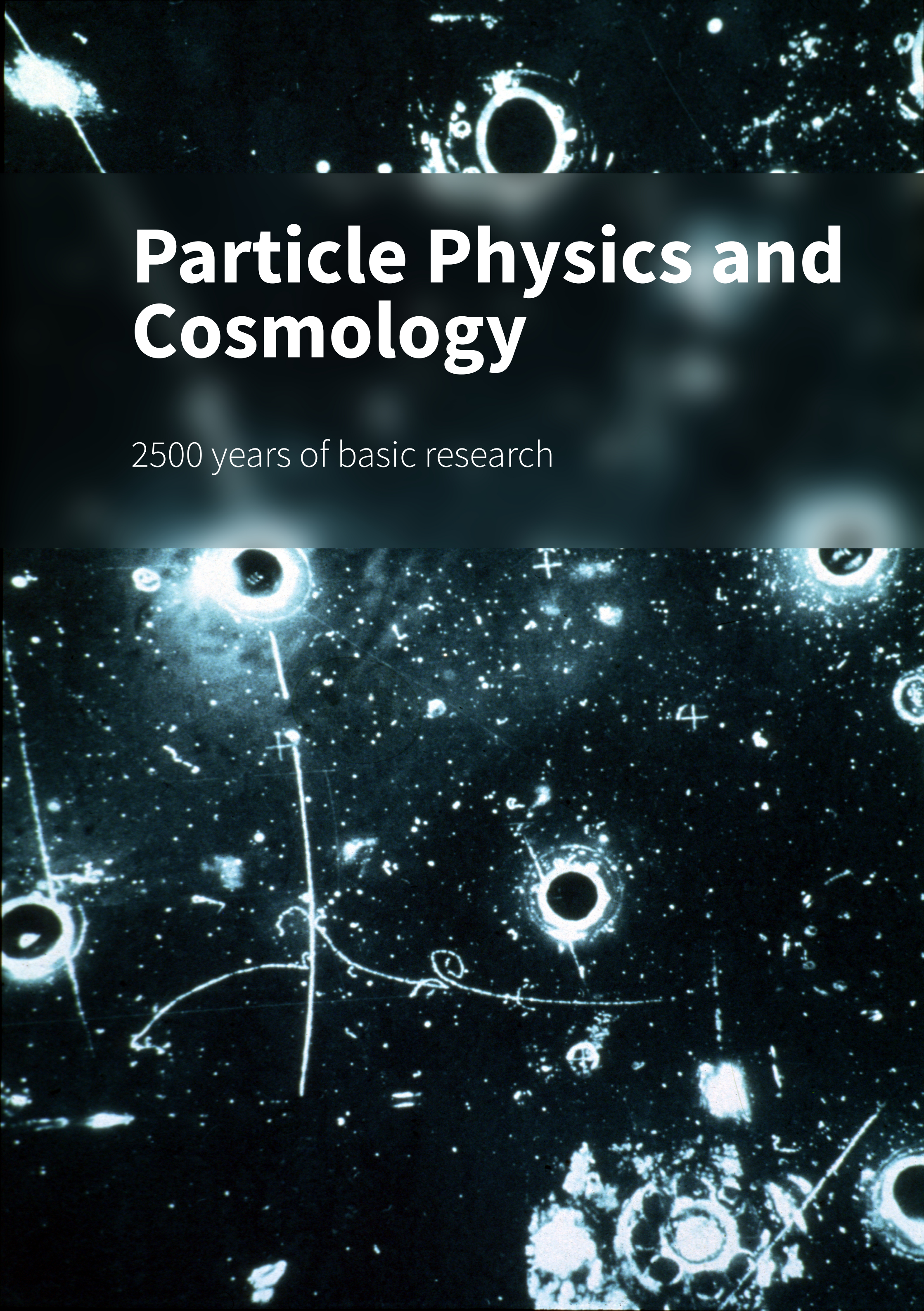


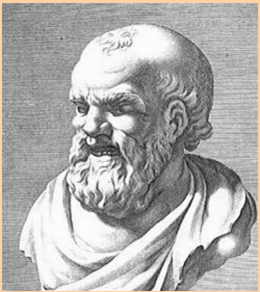
Particle Physics and Cosmology

2500 years of basic research

Front cover: A lepton event - a neutrino interacting with an electron and emerging as a neutrino: first observation of 'neutral currents' in the Gargamelle heavy liquid bubble chamber. (Courtesy: CERN)

This chronology encompasses the end of *ancient history*, the *middle ages* and *modern history*. In this time-frame modern science emerged: *Mythology* branched out into *natural philosophy* which transformed into *natural science*. Natural science today may roughly be grouped into *physical sciences* (such as astronomy, physics and chemistry) and *life sciences* (such as biology and medicine). Formal science (which includes mathematics and statistics) is usually described as a separate category, but provides indispensable tools for reasoning in natural science's different disciplines.

Mathematics and astronomy have their roots in ancient Mesopotamian (on the territory of modern-day Iraq, Syria and Kuwait) and Indus cultures (on the Indian subcontinent). The earliest relevant preserved writings are cuneiform texts engraved in clay tablets from Mesopotamia. They are as old as 4500 years and include elements such as the computation of the square root of 2 (which is the length of the hypotenuse of a right triangle with unit legs) or tables of astronomical events that where interpreted as omens. The roots of modern-day *world religions* can be found in the same cultures.


Wikimedia Commons / Public Domain

Ancient Greek philosophers, like *Democritus* (in Greek Δημόκριτος), develop the idea that ordinary matter is made up of smallest units which cannot be further divided. At this stage the *atom* is merely a *philosophical concept* rather than a theory. It is also controversial at the time. Similar ideas are developed in other ancient cultures.

BC400, Atomism

The Greek philosopher *Aristotle* finishes 'On the Heavens' (in Greek Περὶ οὐρανοῦ), his major work on cosmology. He collects and re-evaluates ideas of earlier Greek philosophers whom he calls *physikoi* ('natural philosophers' or 'physicists') because they seeked natural explanations for phenomena without invoking gods. In his favoured cosmology, Earth is at the centre (geocentric model) and the *four elements* earth, water, air, fire constitute the sublunary sphere (below moon). A *fifth element*, called *Aether*, constitutes the heavens, planets and stars. They exist for eternity and their motion is perfect. The term cosmology derives from the Greek word for world (κόσμος) but will be introduced in this context only much later.

BC350, On the Heavens

The *methods* and *concepts* of mathematics and astronomy have changed significantly since then. In contrast to the old religious texts, which are mostly considered to be of divine origin and thus in principle of eternal validity, the ancient pre-scientific texts (as they are preserved) have no importance for modern natural science. Alongside the development of complex societies, they underwent a kind of evolutionary process until science eventually received a degree of acceptance, as an explanatory approach, comparable to that of the various religions. What emerged differs fundamentally from the origins and will possibly continue to change.

THE way in which this 'scientific progress' evolves was and is controversial. Some argue that it is a continuous process, while others say that it proceeds in steps (revolutionary changes). Some attribute little relevance for the progress of societies, while others say that only scientific progress really exists. Philosophers who discuss these questions study the history of science. The relevance of *technology* for society is evident today. More subtle is the question how far basic research influences technology, culture and politics.

Aristarchus of Samos provides a heliocentric world model in which the sun sits at the centre. Also the apparently fixed position of the stars is explained by their large distance from Earth. Although the original texts will be lost, his idea will be preserved in a citation in *Archimedes of Syracuse*' 'The Sand Reckoner'. However, until the late middle ages, geocentric world models will be dominant.

BC250, Heliocentrism

TECHNOLOGY and science are sometimes contrasted as approaches to *'know how'* ⟷ *'know why'*, respectively. Cosmology and particle physics are the modern disciplines at the extreme right end of this axis. Humans, since before antiquity, had an urge to 'know why' as well, but is this degree of understanding necessary to advance societies? It is worthwhile to confront historical events in the sectors of science, technology and politics to illuminate their relationship. A chronology of cosmology and particle physics can provide the occasion to focus on those events in science and pre-science which were basic (without obvious application) at their time.

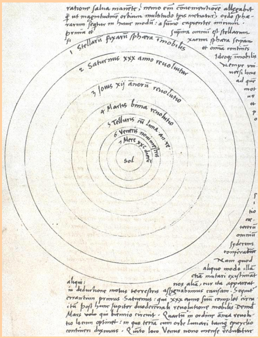
In his 'Doubts Concerning Ptolemy' ('Al-Shukūk ʿalā Batlamyūs'), Alhazen (*Hasan Ibn al-Haytham*) criticises the Ptolemaic model. In particular the idea that an imaginary point, like the *equant* introduced by Ptolemy, governs a planet's motion. al-Haytham will also become known for applying an experimental methodology as he systematically varies parameters to understand their influence on the results.

1028, Doubts Concerning Ptolemy

RELEVANT early foundations of these fields were already motivated by big questions about the motion of heavenly bodies or the character of the cosmos. Simple world models were thought up in attempts to answer them. With the improvement of those models came better understanding of the laws that nature obeys. The methods to study these became increasingly systematic. But, even after they were developed to maturity, science underwent several paradigm shifts in which old concepts had to be replaced by new ones. New generations of researchers, also equipped with a modified cultural background, promoted new theories. The goal to provide natural (in contrast to supernatural) explanations for earthly and heavenly phenomena can be traced far back in time and has remained the same.

Science has its roots in *philosophy*. Its forerunner was and is called 'natural philosophy', a term that goes back to the thinking of a few generations of philosophers of Greek antiquity who, instead of imposing mythological explanations for observed phenomena, tried to find 'natural' ones. They would, for example, postulate that everything originated from a single substance like water (Thales) or that the sun is a fiery stone (Anaxagoras).

These early attempts did not lead them very far, maybe because these so-called 'pre-Socratics' still tried to obtain their conclusions by mere thinking. The viewpoint of Aristotle **[On the Heavens, BC350]**, which was preserved in the form of manuscripts, summarized their ideas. His judgment formed the basis for the thinking until the high mid-ages and was then thought to be compatible with Christian theology. An alternative idea that Earth revolves around the sun, which emerged already early **[Heliocen-**



Wikimedia Commons / Public Domain

Nicolaus Copernicus, a renaissance mathematician and astronomer, puts forward the older idea of a *heliocentric world model* according to which the sun sits in the centre of the universe. At this time, geocentric models are prevailing. Copernicus dedicates his book 'De revolutionibus orbium coelestium' to *Pope Paul III* but delays its publication until the year of his death in apparent fear of the consequences. The publication of his work marks the beginning of a new era, later called the *Copernican revolution*, during which various astronomers will refine the models for planetary and celestial motion.

1543, Copernican Revolution

Public Domain

The English statesman *Francis Bacon* publishes his 'Novum Organum' ('New Method' in English). His ideas will influence the development of the 'scientific method'. They will later be referred to as the 'Baconian method'. This strategy is still *inductive* (a way of reasoning where conclusions are derived from probable assumptions believed to hold true), but he puts emphasis on the use of systematic methods to reveal the cause of a phenomenon.

1620, Baconian Method

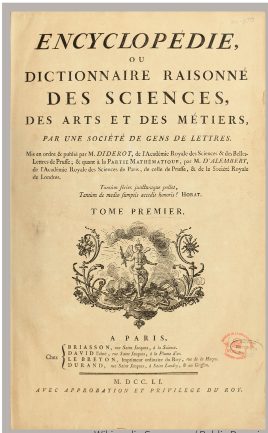
trism, BC250], was disregarded in favor of Aristoteles’ preferred *geocentric model*. On various occasions, later contributors, e.g. **[Doubts Concerning Ptolemy, 1028]**, pointed out that aspects of the astronomical observations could be explained in different, possibly more convincing, ways. When Aristoteles’ conclusions were eventually confronted with sufficiently accurate experimental data, his geocentric cosmology could finally be excluded, ultimately against the resistance of forces that wanted to maintain the status quo.

The subsequent epoch, after Nicolas Copernicus **[Copernican Revolution, 1543]**, showed accelerated progress, and was later called the *scientific revolution*. The empiric rectification of Aristoteles’ hypothesis that took place, became an integral element of the scientific methodology which is systematically applied in modern science. Not because the empirical approach had immediately become common sense, but because individuals understood the benefits of such techniques for research and applied it in their own work **[Baconian Method, 1620]**, **[Cartesian Coordinate System, 1637]**.

In his work ’La Géométrie’, *René Descartes* introduces a *coordinate system* in which the location of objects can be referred to by numbers (the coordinates). The text contains the elements of a two-dimensional coordinate plane which will later become known as the *Cartesian system*. The concept will be important for the forthcoming development of calculus. ’La Géométrie’ appears as an appendix of Descartes’ work ’Discours de la méthode’ which contains the famous quotation ’Je pense, donc je suis’. Descartes puts emphasis on independent thinking. He derives his results from scratch in order not to rely on old, possibly flawed ones.

1637, Cartesian Coordinate System

Science did not evolve independently of society. Its history is one of mutual influence with politics and culture. Philosophy, society’s choirmaster and a mediator of this exchange, knows epochs like Aristotelianism (**[On the Heavens, 350BC]**-**[Copernican Revolution, 1543]**), Enlightenment (approximately (Death of Louis XIV, 1715])-(French Revolution, 1789)), Romanticism (around 1805) and Positivism (1840-1880). These intellectual movements reflected streams in society and, to some extent, influenced the politics, of their own or later epochs. They are also all related to movements in research.



ENCYCLOPÉDIE,
OU
DICTIONNAIRE RAISONNÉ
DES SCIENCES,
DES ARTS ET DES MÉTIERS,
PAR UNE SOCIÉTÉ DE GENS DE LETTRES.

Mis en ordre & publié par M. *DIDEROT*, de l'Académie Royale des Sciences & des Belles-Lettres de Pruſſe; & quant à la PARTIE MATHÉMATIQUE, par M. *D'ALEMBERT*, de l'Académie Royale des Sciences de Paris, de celle de Pruſſe, & de la Société Royale de Londres.

Tantùm ſeries juncturaque pollet,
Tantùm de medio ſumptis accedit honoris! HORAT.

TOME PREMIER.

A PARIS,
Chez BRIASSON, *rue Saint Jacques, à la Science.*
DAVID l'aîné, *rue Saint Jacques, à la Plume d'or.*
LE BRETON, Imprimeur ordinaire du Roy, *rue de la Harpe.*
DURAND, *rue Saint Jacques, à Saint Landry, & au Griffon.*

M. DCC. LI.
AVEC APPROBATION ET PRIVILEGE DU ROY.

Wikimedia Commons / Public Domain

The first book of the 'Encyclopédie', a 'Systematic Dictionary of the Sciences, Arts, and Crafts' is published in France. It will be considered the most important work of the *Age of Enlightenment* ('Siècle des Lumières' in French). During this epoch philosophers like *Denis Diderot*, *Jean-Jacques Rousseau*, *François-Marie Arouet Voltaire Voltaire* and *Immanuel Kant* formulate ideals like liberty, tolerance and progress. Previously unquestioned dogmas are scrutinized with increasing scientific rigour. The intellectual movement is in conflict with monarchy and church. Diderot's co-editor of the Encyclopédie is *Jean-Baptiste le Rond d'Alembert*, a mathematician and physicist who, amongst others, studies and solves the one-dimensional wave-equation which describes for instance the oscillation of a string.

1751, Encyclopédie

THE *Enlightenment* had a profound long-term influence on European societies. Aristocratic doctrines were overthrown and rational reason demanded with increased rigor. Natural philosophers had an influential voice in the philosophical debate **[Encyclopédie, 1751]**. After all, it had been the success of science which exemplified that this rational approach could yield superior results. The Enlightenment had been preceded by the scientific revolution. It began when Aristoteles' geocentric world model, or Ptolemy's more detailed version (Almagest, 150), was confronted with the heliocentric model of Copernicus **[Copernican Revolution, 1543]**.

Wikimedia Commons / Public Domain

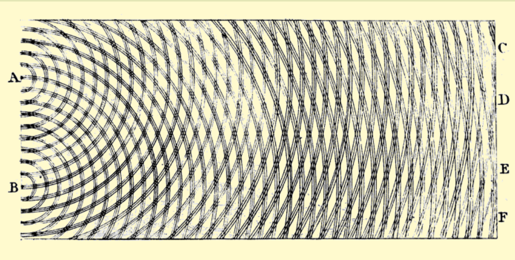
Using a torsion balance, *Charles-Augustin de Coulomb* shows experimentally that the *electric force* between two charges obeys an inverse square law. Remarkably, this is also the distance dependence of *Isaac Newton's universal law of gravity*. However, there are two cases to be distinguished for the electrostatic force. Between charges of the same sign the force is repulsive. For charges of opposite sign it is attractive.

1784, Coulomb's Law

THIS *paradigm shift* may not have been strictly necessary yet, but Kepler used precise measurements by Tycho Brahe and compiled an accurate and detailed heliocentric description of the planetary orbits (Kepler's Laws, 1609). It needed time to acquire acceptance, but was more economic and 'physical' than Ptolemy's picture. The scientific revolution culminated when Newton presented a law of gravity (Universal law of Gravity, 1687) that reproduced Kepler's elliptical orbits when combined with his laws of motion. His formula applied to all known planets, and even to an apple falling from a tree. It featured a gravitational constant and parameters (masses) that differed for those various objects.

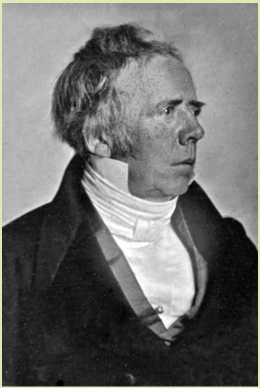
During the age of Enlightenment, the foundations for the *industrial revolution* were laid. The steam engine (Watt Steam Engine, 1776) became the driving force of an unseen advance in societies and an icon of technological progress. The influence of basic science, if it existed, on the development of the steam engine is not obvious. The physical laws of thermodynamics, which accurately describe their operating principles, where developed significantly later **[Carnot Cycle, 1824]**, **[Ideal Gas Law, 1843]**.

Waves have the property that two close-by wave centres (like two stones dropped close by on a lake's surface) lead to a pattern of constructive and destructive interference. *Thomas Young* performs an experiment in support of the wave theory of light. He uses a simple setup in which a light beam is pointed on two small openings in a screen. Each of these acts as a wave center and, indeed, Young observes an interference pattern. The concurrent *corpuscular theory* for light cannot explain this pattern.



Wikimedia Commons / Public Domain

1803, Double Slit



Wikimedia Commons / Public Domain

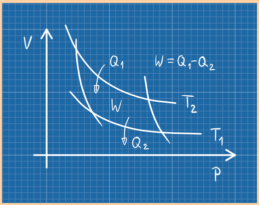
During a lecture, professor *Hans C. Ørsted* discovers that a compass needle changed direction as he switched on and off an electric current from a battery. He realizes the relationship between the electric and the magnetic force. His finding triggers broader interest in electromagnetism. Ørsted also coins the term 'Gedankenexperiment' (literally 'thought experiment') which describes a purely imaginary experiment to investigate the consequences of a hypothesis intellectually.

1820, Electromagnetism

The technological benefits of these scientific results for society arrived only when they were applied to improve the efficiency of combustion engines. A certain common aspiration for progress that came with the Enlightenment may however have facilitated the urge to increase the efficiency of production processes through the use of machines. An important example for science driven progress of technology is the history of *elec-*

tromagnetism. Crucial early contributions (Conservation of Charge, 1747), (Coulomb's Law, 1784), **[Electromagnetism, 1820]**, **[Electromagnetic Induction, 1831]** where basic science. Functional appliances that exploit these physical phenomena came much later (Light Bulb, 1878), **[Alternating Current, 1888]**, but today they form the technological backbone of all modern societies.

SCIENTIFIC discoveries, obtained without obvious application in mind, lead to these advances. The new technologies also enabled more scientific progress. The theoretical developments in electromagnetism culminated in a set of equations that describes all known electromagnetic phenomena **[Maxwell Equations, 1861]**. Remarkably, they did more than just this. They also predicted *electromagnetic waves*, which were systematically searched for **[Electromagnetic Waves, 1892]**, and these experiments were the basis for wireless communication.



Own Work

Steam engines have become widespread over roughly 50 years but a scientific theory describing their properties is largely absent. There is a high interest in improving the efficiency of such engines in order to maximize the mechanical work that can be performed given an amount of fuel (coal). In his only publication ('Réflexions sur la Puissance Motrice du Feu'), the French military engineer *Nicolas L. S. Carnot* describes an idealized *thermodynamic process*. It maximizes the efficiency of heat engines. Later the process will become known as the *Carnot cycle*.

1824, Carnot Cycle

Wikimedia Commons / Public Domain

Michael Faraday demonstrates the principle of *electromagnetic induction*. An electric current sent through a wire wrapped around and iron ring induces a current in a second wire also wrapped around the same ring but electrically disconnected. Faraday will explain the phenomenon in terms of *lines of force* of the fields.

1831, Electromagnetic Induction

MAXWELL was also involved when the ideas underlying modern *particle physics* became concrete. With his help, Boltzmann formulated a microscopic theory for the thermodynamics of gases that relied on atoms or molecules and which yielded the observed macroscopic relationships between temperature, volume and pressure. The existence of atoms (smallest indivisible entities) was speculated on various occasion since ancient Greek history **[Atomism, 400BC]**, but for the first time a physical theory, built on the concept of atoms, made detailed statements about observable quantities. There was no direct evidence for the existence of atoms, however. Mach, who was a proponent of the ’Logical Positivism’ (the scientific branch of the philosophical movement of Positivism), opposed the idea, arguing that atoms represent an unnecessary complication since the relationships of thermodynamics already worked as a phenomenological description **[Boltzmann/Mach Controversy, 1897]**.

The controversy was eventually decided in favor of Boltzmann when experiments began to probe the molecules of gases. These constituents where however found to be divisible themselves (and eventually it was discovered that the elementary constituents of the constituents behaved in a strange way that differed a lot from what was envisaged by Boltzmann). Regular patterns observed in chemistry had provided hints that atoms are composed of smaller quantities (Prediction of Proton, 1815), (Prediction of Electron, 1838). When the atoms where eventually probed in experiments to explore their nature **[Rutherford gold foil experiment, 1908]**, these vague ideas received confirmation, but the early atomic models had to be adjusted significantly to explain the observations made in the new microscopic world. Their complete understanding required a fundamentally different theory that challenged contemporary ideas about the identity of nature, *quantum mechanics*.

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

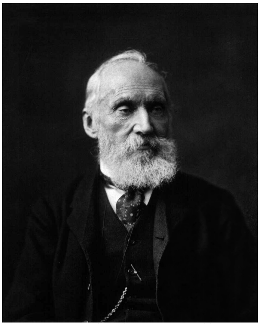
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$$

Scottish physicist *James C. Maxwell* finds a unified mathematical description of electrostatic and magnetic forces. He uses 20 equations which will later be reformulated in compact vector calculus notation. The set of equations describes how electrostatic forces are caused by charges and how magnetic forces result from electric currents. More precisely, they describe the origin and mutual influence of *electromagnetic fields*. These classical force fields are assumed to exist everywhere in space and mediate the respective forces. Maxwell’s equations are a prototype for field theories, the mathematical basis for the description of *particle physics* to be developed. They describe how the space-dependent electric and magnetic fields behave in time. Apart from static fields, which stay constant, they also describe the evolution of *electromagnetic waves* such as light. Implicitly they contain the speed of light as the combination $c = 1/\sqrt{\mu_0 \varepsilon_0}$.

1861, Maxwell Equations

First indications for the conceptional problems ahead came with the discovery that photons can behave like particles (Energy Quantum, 1900), **[Prediction of Photon, 1905]**. This result appeared to be in conflict with the prevailing idea that light behaved similar to water waves **[Double Slit, 1803]**. A theory was in order that could accommodate these seemingly opposite observations. The framework of this theory was completed within Einstein's lifetime, but it represented a serious challenge for his mindset and that of many others. The new theory was probabilistic in nature. This means that it does not allow the precise computation of future events, even if all relevant variables were exactly known. For instance, the position of an electron cannot be known exactly, for principle reasons. One has to live with statements about their probable position given by the absolute value of its 'wave function' **[Copenhagen Interpretation, 1927]**.

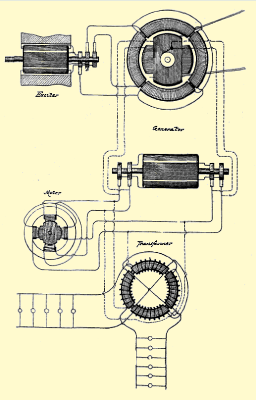


Wikimedia Commons / Public Domain

According to a popular theory by *Lord Kelvin* (William Thomson) atoms are little vortices (swirls) in an aether. The idea is inspired by experiments with smoke rings which where performed by *Hermann Helmholtz*. Kelvin suggests that the vortex theory could explain the observed variety of atoms and chemical bindings between them as knots of such vortices. His ideas will spark the new mathematical field of *topology*

1867, Kelvin's Vortex Theory

WHAT is precisely known is the equation which describes the evolution of such wave functions. Various physicists have opposed the departure from *determinism* implied by the quantum theory and some proposed alternative theories that attempted to resolve the issues. However, the commonly accepted picture became the Copenhagen interpretation **[Copenhagen Interpretation, 1927]** which accepts the quantum equations as a given fact. No observed phenomenon was found to be inconsistent with this pragmatic viewpoint. This includes the detailed physics of atoms as well as the latest findings in elementary particle physics.



Wikimedia Commons / Public Domain

The Yugoslav inventor *Nikola Tesla* is awarded US patents for the electric generator and an electric motor using *alternating current* (AC). His inventions exploit the principle of electromagnetic induction, discovered by Faraday 50 years earlier. Tesla had proposed his ideas for AC power transmission to *Thomas A. Edison* who however wanted to realize his own system based on direct currents (DC). The conflict will result in what will be remembered as the *War of Currents*. The war will be decided for Tesla's AC system as soon he builds an electric power plant at the Niagara Falls. The produced energy will be transmitted to supply New York with electrical power. This could not work with DC currents that cannot be transformed to the high voltages needed for efficient transfer over long distances.

1888, Alternating Current

Quite in contrast, the, seemingly random, theory has predicted the values of some of the most accurately measured quantities.

Wikimedia Commons / Public Domain

Two years before his death at the age of 36, *Heinrich Rudolf Hertz* publishes his experiments about the propagation of electromagnetic force. The subject of his PhD thesis had been to check if the theoretical description given by Maxwell was correct. This abstract mathematical theory predicted the existence of electromagnetic waves. Hertz managed to generate and to detect these waves experimentally. The older idea that the electromagnetic force acts instantaneously is now excluded. Remarkably Maxwell's equations describe the propagation of electromagnetic waves, even though they were only meant to account for various electromagnetic phenomena in which electric charges or currents acted as sources. Hertz's experiments also lay the foundation to the transmission of radio signals (wireless telegraphy).

1892, Electromagnetic Waves

FOR a complete quantum description of the smallest known particles, quantum mechanics had still to be generalized. In particular, it had to be combined with the *special theory of relativity*, which emerged at the same time, for consistency reasons (such that it applied to particles that were simultaneously very small and very fast). Similar to the developments after the unification of electrostatic and magnetic force by Maxwell, this fusion had serious theoretical consequences. One of them was the prediction of antimatter, which could indeed be identified in experiments (Prediction of Positron, 1928). A second important step was to incorporate it in a *field theory*, precisely like Maxwell's theory of electromagnetism.

THE reward for these efforts was *quantum field theory* (QFT) **[Quantum Electrodynamics, 1927]**. QFT was to become the leading conceptional framework for modern physical theories. It describes particles as tiny ripples on fields that permeate all space. Separate fields exist for the photons (the particles of light) and the electrons. The properties of the theory are such that only ripples with specific energy (quanta) can be excited, such that a relationship between their energy and their velocity is always satisfied. In addition, there may be thought to be *virtual quanta*. They are different in that they can violate this relationship between energy and velocity if they exist only for very short time. These principles reflect the laws of quantum mechanics.

Many of the physicists who contributed to these developments were also involved in the American *nuclear bomb* program **[Einstein–Szilárd Letter, 1939]**, (Hiroshima and Nagasaki, 1945). The insight that this new type of weapon, which exploits the large amount of energy freed in the fission of heavy nuclei in a chain reaction, could be built came inevitably with the understanding of the relativistic quantum theory (Szilárd is said to have had this idea while waiting for a traffic light to turn green). The completion of the new weapon had the known consequences for the post-war history.

The Swedish scientist *Svante Arrhenius* publishes his article 'On the Influence of Carbonic Acid in the Air Upon the Temperature of the Ground'. He derives a relationship that quantitatively describes the *Greenhouse Effect*. Heated by sunlight Earth's surface emits thermal radiation. This radiation is absorbed (and partially reflected) by the atmosphere. The effect increases if gasses like CO_2 are added. He understands that the burning of fossil fuel by humans can cause global warming. The model he uses will need to be refined by the inclusion of further effects, but the qualitative result will not change. Arrhenius had received a grant that allowed him to travel and to work with influential scientists like *Ludwig Boltzmann*. He will become best known for the *Arrhenius Equation* which describes the inverse exponential dependence of reaction rates on the ratio of activation energy and temperature.

1896, Greenhouse Effect

After a lecture given by Boltzmann, *Ernst W. J. W. Mach* declares 'I do not believe that atoms exist!'. His philosophy is that things that cannot be perceived are not real or not needed for physical theories. At the time atoms are hypothetical as their effects cannot be observed directly experimentally. Boltzmann, who defends *Atomism*, will, years after, hang himself in a state of depression. Later his controversy with Mach will sometimes be made responsible for his depression but when he committed suicide his opponent had already resigned, due to illness, from his post at the University in Vienna where both worked.

Wikimedia Commons / Public Domain

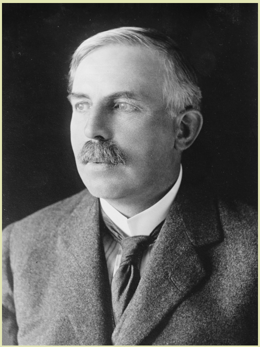
1897, Boltzmann/Mach Controversy

A further deep technical challenge to be overcome on the road to a consistent theory was saved until after the war and related to the virtual quanta that appeared in QFT's. Their mathematical contribution to observable quantities was found to be unbounded (infinitely large). This problem represented a serious challenge for particle theory, since it meant that no use could be made of the computed results (Lamb Shift, 1947). Some started to consider QFT's irrelevant. However, the solution came with the successful application of QFT explaining experimental observations made of the electrical conductivity of metals at low temperature (Renormalization, 1974).

EVEN though most building blocks of modern particle physics existed, a lot of work had still to be done. But, with the new large-scale collaborations, research had entered the age of *big science*. Large nuclear and particle experiments were now funded directly by the state, in the west and in the east, and science progressed at even faster pace. A plenitude of hitherto unknown particles was discovered. Some of them were found to occur naturally in the air showers of cosmic rays, others were produced as particle colliders smashed ions (atoms that were stripped-off some of their electrons or other charged particles) on a variety of targets. The ever increasing energy of these ion beams allowed the creation of heavier and heavier particles. Improved detectors registered even the very short lived particles, or at least the products of their decays.

When light shines on metals these can release electrons. Strangely, this effect (the 'photoelectric effect') is seen only if the light has a minimum frequency ν, independent of its intensity. *Albert Einstein* finds that this detail can be explained if it is assumed that light consists of discrete wave packets of energy $h\nu$, where h is the constant introduced by *Max K. E. L. Planck* five years earlier. The predicted discrete energy packets are light-particles, photons. This particle character comes as a surprise since light has until then mostly be treated as electromagnetic wave.

1905, Prediction of Photon

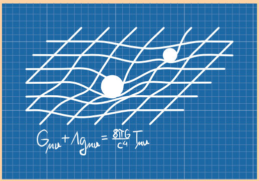

Wikimedia Commons / Public Domain

Ernest Rutherford (with *Hans Geiger* and *Ernest Marsden*) discovers *atomic nuclei*. In their experiment a beam of α-radiation emitted by radioactive substances is pointed on a thin gold foil. They show that most α-particles are only slightly deflected, while a small number is scattered strongly. This allows the conclusion that the mass of the gold foil is concentrated in small nuclei and most ions pass through the empty space between them. A few α-particles hit directly on nuclei and get deflected strongly. The older *plum pudding model* can now be excluded. The experiment already has many of the features of future experiments, a particle beam, a target (gold foil) and a detector.

1908, Rutherford gold foil experiment

SOME of the new particles and their properties came as a complete surprise, e.g. (Muon, 1936), (Kaon Decays, 1964), but many where predicted before they were identified in experiments, e.g. (Prediction of Pi Meson, 1935), (Quarks, 1964). Theorists reacted and accommodated the new ones quickly in their models. The emerging theory included all the elementary particles (those which are not seen to be composed of others) and described all known fundamental interactions between them (except gravity) in an elegant way. This theory was dubbed the *standard model* and is represented by a long expression (the so-called lagrangian) composed of abstract mathematical operators (symbols that obey certain mathematical relationships) which represent fields and the corresponding particles. It is accompanied by a set of concepts which tell physicists how to compute observable quantities. The lagrangian also contains a number of parameters such as the masses of particles or constants that define the strength of the interactions. They can, at present, not convincingly be derived from physical principles.

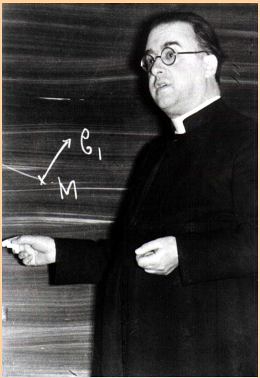
Einstein presents his ’field equations of *general relativity*. They describe how matter (or more generally energy) influences (curves) the geometry of space-time.


$G_{\mu\nu}+\Lambda g_{\mu\nu}=\frac{8\pi G}{c^4}T_{\mu\nu}$

Own Work

The curvature, in turn, determines the apparent gravitational force exerted on massive objects. This makes general relativity a theory of gravity. A conceptional advantage over Newton’s law is that they avoid the ’instantaneous action at a distance’ between two separated objects. The equations are formulated in the mathematical language of *differential geometry*. According to it, the space-time coordinates we are used to, three spatial coordinates and one for time, can be used only locally. This means that they need to be transformed (in a specific manner) if we compare our local time or position with that of other distant objects or events. One may say that the coordinates are (only) relative, i.e. dependent on the observer.

1915, General Theory of Relativity



Wikimedia Commons / Public Domain

The priest and physicist *Georges H. J. É. Lemaître*, employed at the Catholic University of Leuven in Belgium, presents his idea of an expanding universe in a paper entitled (in English translation) ’A homogeneous Universe of constant mass and growing radius accounting for the radial velocity of extragalactic nebulae’. It contains the key idea that the galaxies recede from each other due to an expansion of the universe. It suggests the *Big Bang*. Einstein rejects the concept since he prefers the idea of a stationary universe.

1927, Big Bang

THE 20th century also saw the development of *big bang* cosmology. The theory of general relativity **[General Theory of Relativity, 1915]** provided the appropriate framework. It allows to compute the evolution of the universe if the amount and type of matter it contains can be specified. Astronomical observations were consistent with the simplifying assumption that the universe looks the same observed from any position within (in agreement with the Copernican principle according to which we do not occupy a preferred place in the cosmos), but demanded that the universe is expanding. This suggests that it started from a hot and dense initial state **[Big Bang, 1927]**.

At sufficiently early times the temperatures of the early universe are so high that even the heavy and short-lived particles discovered in collider experiments must be abundant. Scientists therefore began to apply the uncovered principles of particle physics to the big bang and found that they could accurately describe important observations such as the abundance of chemical elements **[Primordial Nucleosynthesis, 1948]**. A number of sophisticated astronomical experiments returned increasingly precise data. Because light has a finite speed, information from distant stars that reaches Earth today was emitted in the distant past. Observing distant stars therefore also means looking back in time. The oldest electromagnetic signal that can be received is the *cosmic microwave background* (CMB) **[Cosmic Microwave Background, 1964]**. It was measured with high precision by satellite experiments (Wilkinson Microwave Anisotropy Probe, 2003).

From its inception, *quantum mechanics* challenged physicists and philosophers. While classical physical theories are deterministic (the future evolution of any system can, in principle, always be predicted accurately), quantum mechanics has *probabilistic properties*. They are inherent to the *wave-function description*. For properties of systems, like the position of a single particle only statistical statements can be made. In this example, the wave-function describes the probability to find the particle in a certain interval. *Niels Bohr* and *Werner Heisenberg* accept the wave-function as physical reality. It can however not be measured directly. Whenever a measurement (an observation) is made, the wave-function collapses and a specific value is measured for the particle's position. The picture, later called the *Copenhagen interpretation*, is controversial but is to become the most widely accepted picture.

1927, Copenhagen Interpretation

The latest generation of experiments in particle physics and cosmology strikingly confirmed theoretical concepts that had become mainstream among scientists. Specifically, the *Higgs particle* has been identified at the LHC (Higgs Boson, 2012) and, so far, seems to be fully consistent with predictions. Precise measurements of the fluctuations in the cosmic microwave background are consistent with the paradigm of *cosmological inflation* (Planck Satellite, 2014). Finally, LIGO has claimed to having detected directly *gravitational waves* as predicted 100 years ago by Einstein on the basis of the theory of general relativity. Even though this does still not prove the correctness of these theories, it shows that the international theoretical physics community as a whole can find broad agreement on the concepts and make predictions that are reliable enough to guide the design of new experiments. The obtained models represent certainly excellent mathematical fits. They compress numerous complex phenomena in a moderate number of equations and parameters.

To obtain these predictions, physicist have relied on what has been called the 'Unreasonable Effectiveness of Mathematics' **[Unreasonable Effectiveness, 1960]**. Mathematical models were built to describe the known phenomena. Their consistent formulation required the model builders to introduce new concepts that, in turn, led to successful predictions about the yet unknown (for example new particles). This poses the philosophical question if nature is fundamentally mathematical, i.e. whether it truly obeys mathematical principles. If mathematics is looked at as a mere tool, invented by humans to make sense of what they observed in their environment, it seems unreasonable that this be the case.

In his 'The Quantum Theory of the Emission and Absorption of Radiation', *Paul Dirac* lays foundations for *quantum electrodynamics*. This theory will become the prototype for successful theories of *particle physics* like the *standard model*. Dirac describes the interaction between matter and radiation by mathematically decomposing the continuous electromagnetic field into an ensemble of *harmonic oscillators*. He introduces quantum mechanical operators (mathematical objects) that can formally create or annihilate particles. This is crucial since the quantum theories so-far where able to describe the strange behaviour of small particles but not how these are created or change type. Several other physicists will contribute in the coming years and establish the theory of quantum electrodynamics. Perturbation theory can be used to obtain physical predictions from the theory, but it will soon turn out that these computations can lead to false, or at least unreliable, results. This observation will lead to the development of the so-called *renormalization theory*.

1927, Quantum Electrodynamics

Philosopher *Karl R. Popper* publishes a book that describes his *philosophy of science*. According to Popper scientific theories cannot strictly be proven to be correct. However, it may be possible to prove theories wrong empirically (by making a single observation that is in conflict with the predictions of the theory). This insight suggests distinguishing between theories that are falsifiable (those which can be disproved) and others. Many physicists will adopt this concept and regard theories which cannot be falsified as nonscientific. The concept will be challenged as new theories are developed that are out of reach of realizable experiments and may be proved wrong in principle but not in practice.

1934, The Logic of Research

In theoretical particle physics and cosmology today there exists a multitude of highly speculative ideas that are mutually exclusive, or at least not plausibly realized at the same time. Many of these ideas try to exploit this strategy. Based on the set of concepts that were established in the construction of the standard model, researchers have proposed modifications by merely generalizing one or more of its building blocks, e.g. (Extra Dimensions, 1914), **[Supersymmetry, 1971]**). Promising candidates fulfill the constraint that they reduce to the standard model in the respective limit. Among these, extensions that are mathematically elegant are usually preferred by the physics community. A second common strategy is to break principles underlying the standard model to see when such modifications lead to observable results.

Since the present generation of experiments did not yield tangible discoveries beyond those which confirmed the theories already backed by a majority, some worry that future progress may be hindered because hints for were to look are missing. On the other hand these experiments did precisely what is required for progress, according to the principles of the scientific method: They falsified (proved wrong) alternative models that predicted deviations **[The Logic of Research, 1934]**. Serious long-standing problems with the established standard model remain anyway: By energy, most of the content of the universe does not have a verified theoretical explanation. Neither the origin of *dark energy*, nor that of *dark matter* is understood conclusively, and *neutrinos* (feeble partners of the electron, muon and tau particle) have vanishing masses in the standard model, but not in experiments. These questions are tackled by recent *theories beyond the standard model*, but none of the candidates is agreed upon by a large majority of physicists.

Leo Szilárd writes a letter to US president *Franklin D. Roosevelt* which is signed by Einstein. Szilárd had realized that the fission of heavy nuclei could lead to a nuclear chain reaction. German and Austrian scientists had discovered nuclear fission and, therefore, the authors point out the risk that Germany could develop atomic bombs. The letter is taken very seriously by the US government and eventually it will start Americas own nuclear program with the *Manhattan Project*. Einstein will later regret signing the letter and be quoted with saying ’Had I known that the Germans would not succeed in developing an atomic bomb, I would have done nothing.’.

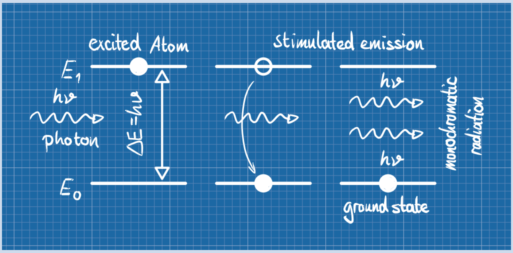
1939, Einstein–Szilárd Letter

In his PhD project, *Ralph Alpher* worked out a theoretical explanation for the observed light chemical elements based on the assumption of a hot Big Bang cosmology. His results are now published in a paper later called the $\alpha\beta\gamma$-paper after its authors Alpher, Bethe and Gamow. The story goes that *George Gamow* had intentionally invited *Hans Bethe* to join when he realized the coincidence. The process of *primordial nucleosynthesis* starts, when the universe is sufficiently cold, with the fusion of hydrogen to Deuterium. Helium and small amounts of Lithium isotopes are produced subsequently. The theory will become one of the pillars of particle cosmology. When dark matter is added to the primordial soup it accurately predicts the observed abundances of light elements.

1948, Primordial Nucleosynthesis

Basic science has not been kind to human vanity. In the spanned time interval, mankind had to move intellectually from the center of the cosmos to an orbit around one of about 200 billion stars, in one of up to 200 billion galaxies in the visible universe. The 200 thousand years long history of the human civilization lasted only a blink of an eye compared to the 14 billion years of cosmic expansion in a hot big bang. This evolution continues today, at an increasing rate, and has been predicted to go on forever. The resulting dilution of the interstellar medium, it seems, will cause it to fail in providing sufficient amounts of fuel for the formation of new stars. If true, ultimately any civilization will become extinct in the very distant future (100 trillion years).

The theoretical concept for the Laser (laser stands for 'light amplification by stimulated emission of radiation') is published by two researchers at Bell Labs. The concept is based on a quantum phenomenon, the *stimulated emission of radiation*, for which the theoretical foundations where laid out by Einstein. A few years earlier, a device, based on this effect but using microwaves, the maser, was invented. Some quantum physicists assumed that it could not work, assuming that it would violate Heisenberg's uncertainty principle. Within three years the first working (infrared) laser will be built. The highly collimated light beams it produces will find a plethora of applications in science and technology.



Own Work

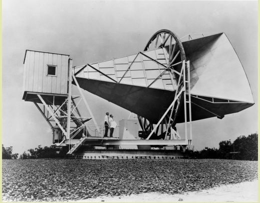
1958, Laser

Yet, some argue that our universe is a very special place. Namely, all the physical laws we know depend on the presence of observers like us. If we were not here, nobody would study them. Therefore, our universe should be such that it allows the existence of observers at some stage of its evolution. If, for instance, the density of matter is too low, no stars or planets could form, and no life can come into existence.

The particle physicist *Eugene Wigner* publishes an article entitled 'The Unreasonable Effectiveness of Mathematics in the Natural Sciences'. It discusses the commonly perceived phenomenon that mathematical descriptions of science problems often lead to further scientific progress. If the mathematics in use is assumed to be merely a man made method to describe physical phenomenon, rather than the true language of nature, this observation appears as a miraculous coincidence.

1960, Unreasonable Effectiveness

Out of the many different universes, which are in principle possible in agreement with the physical laws, only few will presumably support the emergence of life able to make such observations. This reasoning may sound like a tautology (and maybe it is), but interpreting it in a strict way **[Anthropic Principle, 1973]** one could conclude that there is no need to search for physical explanations for the fundamental parameters of the theory. Supporters of the so-called *multiverse hypothesis* argue that all the different universes, characterized by different sets of parameters, are actually created during cosmological inflation, and that we happen to live in one of a few which support life. This approach might explain *why* the parameters have the values they have but it would still not tell us *why* the equations that contain these parameters have the form they do.


Wikimedia Commons / Public Domain

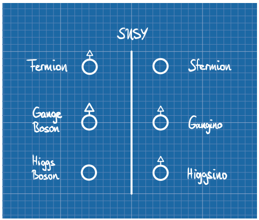
Arno Penzias and *Robert R. Wilson* are trying to improve a sensitive Horn Antenna which they want to use for an innovative communication satellite project. After cooling the receiver of the antenna to below 4K, they note the presence of a faint but steady noise. They try to locate the source and, amongst others, remove a pigeon’s nesting. By chance, they hear about an idea to detect remnant microwave radiation originating from the *Big Bang*. The Soviet astrophysicists A. G. Doroshkevich and *Igor Novikov* were the first to propose this possibility earlier that year. They realize that what they measured can be explained by the cosmic microwave background radiation (CMB), the remnant of a hot early stage of the universe which was red-shifted due to the cosmological expansion. Their discovery therefore disfavours the competing steady state theory according to which the universe always existed in the present state. The observation of the CMB convinces most cosmologists that the universe began with a hot *Big Bang* and will turn out to offer means to measure various parameters of the universe with unprecedented precision.

1964, Cosmic Microwave Background

The technological advances did not only bring the increased live expectancy of individuals in western societies, and their freedom to use a large fraction of it for activities that are not directly their own sustainment. They also enabled mankind to bring itself to the brink of extinction. Researchers who laid the foundations for modern science that continue to shape our mindset have also aided the development of *nuclear weapons*. Modern mega-cities lie within the zone of total destruction of the largest hydrogen bombs developed since then. The theoretical understanding of these weapons was tightly linked to developments in basic science. The concepts of quantum mechanics and relativity which made fission and fusion bombs possible are also basis for of some of the gadgets which we use every day, e.g. **[Laser, 1958]**, (Global Positioning System, 1995) and more such devices are under development.

At the same time, *nuclear power* became an important source of electricity for the energy-hungry societies. There are ongoing efforts to turn the fusion process that powers existing hydrogen bombs as well as the sun into a new source of electrical energy. Such technology would neither be infinitely available nor 100% clean, but it could beat conventional power sources in these respects, and might provide a realistic chance to meet ambitious climate goals. Chances and risks of basic research can go hand-in-hand.

Scientific ideas according to which the man-made emission of climate gases (CO_2 specifically) influences the terrestrial temperatures are remarkably old **[Greenhouse Effect, 1896]**. One of the long-term benefits of the scientific progress for society is that *climate change* has meanwhile been recognized as a major challenge. The models that form the basis for climate predictions and their evaluation make use of large portions of the modern science machinery. Man made or not - scientific evidence mounted that the global temperatures are increasing, and there is also broad agreement that this change could proof to be very harmful. In so far, the primary question to be debated is which measures are appropriate to tackle the problem - a serious and versatile challenge for science.



Own Work

The idea of a Supersymmetry in quantum field theory (SUSY) as an extension of the space-time symmetry is born. Several teams make independent contributions (*J. L. Gervais* and *Bunji Sakita*, as well as *Yu. A. Golfand* and *Evgeny P. Likhtman* publish in 1971). The first realistic SUSY model, called the Minimal Supersymmetric Standard Model, will be proposed 3 years later. An important prediction of SUSY is that all standard model particles have a SUSY partner. This partner has integer (or half-integer) spin if the standard model particle has half-integer (or integer) spin. If SUSY were a perfect symmetry these additional particles would have the same masses as their partners. Since none of these particles is known, SUSY must be broken such that they may be much heavier. It will become evident that the question of how SUSY is broken does not have a unique answer and that this ambiguity adds significant uncertainty concerning its predictions.

1971, Supersymmetry

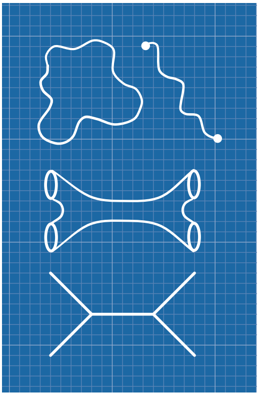
Scientific results have never been absolute. They were looked upon differently in post-view and often they had to be discarded (the poster accounts for only some of such failed approaches, e.g. **[Kelvin's Vortex Theory, 1867]**). Many scientists throughout the centuries were inspired by the idea to obtain a perfect and universal ’theory of everything’. What they achieved were partial solutions which were compatible with observations for a period of time. It is quite possible that future developments will bring more paradigm shifts.

At a conference, 500 years after Copernicus’ birthday, *Brandon Carter* introduces the ’Anthropic principle’. According to him, even though our position in the universe is ’not necessarily central, it is inevitably privileged to some extent’. Namely, our universe must be such that it allows our existence as observers. He distinguishes a weak form ’we must be prepared to take account of the fact that our location in the universe is necessarily privileged to the extent of being compatible with our existence as observers’ and a strong form ’the universe (and hence the fundamental parameters on which it depends) must be such as to admit the creation of observers within it at some stage. To paraphrase Descartes, cogito ergo mundus talis est.’ of the anthropic principle. Various modifications of the anthropic principle will be proposed. While physicists tend to agree with its weak form, the strong form is controversial.

1973, Anthropic Principle

Its accelerated progress has - at least subjectively - brought fundamental science ahead of philosophy. Many scientists feel that the application of the scientific method sets science apart from philosophy, and other approaches, in the competition for the answer to the big questions. One of the major conceptional challenges today is considered to be the unification of gravity and quantum theory. Einstein’s theory of general relativity describes gravity as an effective force mediated by the curvature of space-time. It is insofar quite different from other fundamental forces and no established consistent quantum theory is known. A leading candidate is string theory **[String Theory, 1984]**. However, it introduces concepts that can possibly never be probed in experiments because accelerators that reach sufficiently high energies are not realistic.

The theory may therefore not be falsifiable in practice. Opponents of string theory argue that it should be called unscientific because it does not conform with the scientific method. However, this method is a rather loose collection of principles which is defined by how scientists proceed in their practical work, rather than a strict rule. It emerged within 2500 years as a functioning procedure. Proponents of string theory consequently reply that the scientific method should be changed in that the falsifiability criterion is softened, if further progress becomes impossible otherwise. In the eyes of its opponents this would mean essentially that science becomes philosophy - which is where it came from.



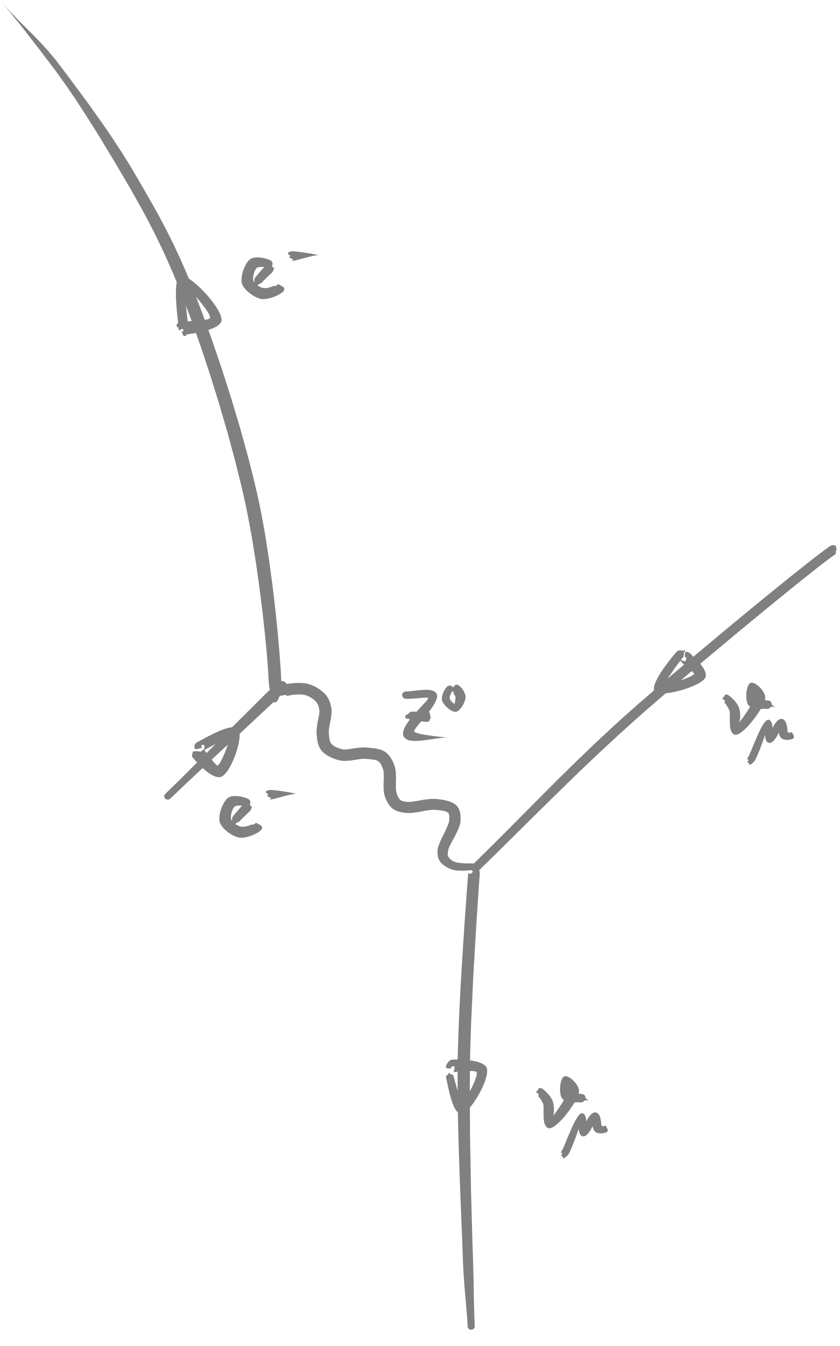
Own Work

One of the shortcomings of the Standard Model of particle physics is that it does not accommodate a *quantum theory of gravity*. The search for such a unified description of all interactions (sometimes called the *Theory of Everything*) is one of the greatest theoretical challenges. The candidate which will be seen as the most promising idea is *String Theory*. In this framework, elementary particles are replaced by one-dimensional (mathematical) objects, called strings, in high-dimensional spaces. *Edward Witten* works out several important consequences of this concept. Many will follow in his footsteps and establish string theory as a new active branch of high-energy physics. However, it will remain difficult to obtain applicable results.

1984, String Theory

Today, science is a highly institutionalized and competitive discipline. In most fields there is a high degree of international collaboration. *Particle physics* and *cosmology* are two of the spearheads of present-day research. Activity in these fields exists in most modern industrial countries. 49% of all 109 Nobel prizes in physics were awarded for fundamental research (39% in the categories particle physics, cosmology and astronomy). 79 out of the worlds 100 top-ranked universities (Leiden size-independent ranking 2015) have one or more dedicated particle physics or cosmology *theory* group(s). These institutions typically cover a broad range of basic and applied research. Practitioners, at any position on the 'know how' ⟷ 'know why' axis, today employ scientific methods or the tools that resulted from centuries of scientific progress.

While the big experimental efforts in the field directly exchange know-how with leading-edge technology, most theoretical particle physicists and cosmologists would likely deny the practical applicability of their research. However, the basic theoretical foundations of modern science, laid only 100 years ago, led to a plenitude of applications that were not foreseen by the founding fathers either. Fundamental research additionally influences societies through its contributions to culture. Elements of modern scientific concepts like relativity or the big bang have become common knowledge and influence human self-perception. Others, notably those of the quantum theory, are still less known. This is remarkable, because it makes profound statements about the character of nature. The smallest known elements, which once determined the fate of the whole universe, behave in a way which appears to be indeterministic and often counter-intuitive, quantitatively tangible only with the help of abstract mathematics.



Andreas Hohenegger for the *UiS Cosmology Group*, February 2016